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Effect of Ethanol Additives on Combustion and Emissions of a Diesel Engine Fueled by Palm Oil Biodiesel at Idling Speed

Guirong Wu, Jun Cong Ge * and Nag Jung Choi *

Division of Mechanical Design Engineering, Jeonbuk National University, 567 Baekje-daero, Deokjin-gu, Jeonju-si, Jeollabuk-do 54896, Korea; wgr@jbnu.ac.kr

* Correspondence: jcge@jbnu.ac.kr (J.C.G.); njchoi@jbnu.ac.kr (N.J.C.); Tel.: +82-63-270-4765 (N.J.C.)

Abstract: Biodiesel is known for its high cetane number and high oxygen content among other advantages, but its high viscosity and density are not trivial issues for fuel flow and atomization, especially under idling conditions. Due to low cylinder temperature and incomplete combustion, engine idling is one of the worst operating conditions. As a common fuel additive, ethanol can address some of the shortcomings of biodiesel. This work evaluated the combustion and emission characteristics of different concentrations of ethanol additives on a diesel engine fueled with palm oil biodiesel under idling conditions. The results show that ethanol helps to increase peak cylinder pressure and heat release rate, suppressing the production of certain emissions with a maximum reduction in smoke opacity of 71%.

Keywords: biodiesel; ethanol additives; idling speed; engine performance; combustion and emission characteristics

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1. Introduction

Diesel engines provide ample power for transportation, power generation, agriculture, and other fields. However, engines also consume a large amount of petroleum reserves, and the emissions released have adverse effects on the environment and humans [1]. With the increasingly tight fossil fuel reserves and stringent long-term emission standards for vehicle diesel engines, researchers have begun to explore clean resources that can reduce fossil energy dependence [2]. Among the existing diesel alternative fuels, biodiesel has been an object of attention of researchers. Biodiesel is a clean and renewable fuel that can be made from waste vegetable oil, animal fat, and non-edible vegetable oil through a transesterification process [3]. Compared to diesel, biodiesel is non-toxic, does not contain sulfur, and is biodegradable [4]. Due to the special structure of its main component fatty acid esters, biodiesel normally contains 10–15% oxygen [4], which helps to more fully oxidize the fuel. Ge et al. analyzed the exhaust gas of a blend of biodiesel and diesel, finding that adding 20% biodiesel to diesel reduces volatile organic compound emissions [5]. However, there are some shortcomings of biodiesel including its higher density and viscosity, which adversely affect fuel flow and injection [4]. Mayo et al. found in the test that due to the deterioration of atomization and evaporation conditions, B100 (100% soybean biodiesel) has a larger droplet size and a longer injection depth during the injection process [6]. Secondly, biodiesel is more corrosive than diesel, and the deposits and corrosive acids produced may aggravate engine wear [7]. Biodiesel contaminants may clog filters, fuel injectors, and aggravate the corrosion of the fuel system and the degradation of elastomer materials [8]. Fortunately, these shortcomings can be compensated for by adding suitable additives to biodiesel.

There have been many studies to change the physicochemical properties of biodiesel using additives. According to a report [9], metal-based additives, cetane number additives, and oxygen-containing additives have been used to improve the properties of biodiesel such as viscosity, flash point, and volatility, which help to improve combustion quality and reduce the generation of related pollutants such as soot. Kannan et al. added $FeCl_3$ at different concentrations as a metal-based additive to waste cooking palm oil biodiesel, where it was observed that the cetane value and flash point of the fuel improved slightly, accompanied by reductions in HC, CO, and flue gas emissions [10]. Kumar et al. tested the effect of cerium oxide additives on B20 (20 vol% waste cooking oil biodiesel + diesel) under different injection pressures and found that CeO_2 additives shorten the ignition delay of the fuel and increase the maximum thermal efficiency of the engine by 2.5% [11]. However, a qualified fuel additive should not only produce beneficial effects, but also be cost effective and impart low environmental impacts. As a common fuel additive, ethanol can be derived from renewable or discarded agricultural raw materials such as corn and wheat with good economic efficiency [12–14]. Although ethanol is not an ideal alternative fuel for diesel engines, it can be added to reduce fuel viscosity, cetane number, and flash point as well as increase fuel volatility and improve cold flow performance [15].

The scope of research involving ethanol additives in biodiesel or fossil diesel is relatively extensive. In a spray characteristics experiment conducted by Zhan et al., adding 20% soybean biodiesel to diesel increased the characteristic droplet size of the spray; however, after adding 20% ethanol, the droplets were optimized to the level of pure diesel [16]. Zhu et al. explored some characteristics of ethanol-biodiesel blended fuels under five loads of 0.08, 0.2, 0.38, 0.55, and 0.70 MPa on an inline four-cylinder engine. They demonstrated that ethanol promotes higher pressure, increased heat release rate, and decreased emission of BSNOx [17]. Pradelle et al. tested the effects of 0, 1, and 2 vol% ethanol additives on the physical and chemical properties of diesel-biodiesel-ethanol blends and found that low concentrations of ethanol helped to slightly reduce the viscosity, density, and surface tension of the fuel as well as slightly increase the cold filter plugging point [18]. Madiwale et al. added ethanol to jatropha, soybean, palm, and cottonseed biodiesel containing 5 vol% diesel and found that braking power and braking thermal efficiency were improved, but braking-specific fuel consumption increased [19]. It can be seen that ethanol additives may have obvious effects in different ratios, multiple biodiesel and different test conditions.

When the engine is in the idling state, the accelerator pedal is not pressed down and the engine runs at a low speed, during which the output power only meets the working requirements of the water pump, generator, air conditioner, and other accessories. Under idling conditions, an engine cannot operate at a suitable temperature and the combustion quality is poor, which leads to increased emission levels [20]. Meanwhile, the fuel consumption of the engine and the NOx, HC, CO, and other gas emissions are much higher than those in the driving state [21]. Although it is not unusual for ethanol to appear as an additive in blended fuels, the performance of ethanol-biodiesel fuel under idling conditions of diesel engines needs to be supplemented.

Palm oil is the main bio-oil species in Asian countries such as Malaysia and Indonesia [22]. Unlike other common raw materials such as soybean and rapeseed, palm is a perennial plant that can continuously produce biodiesel. Palm is not only the raw material with the highest oil yield [23,24], but also has outstanding performance in terms of productivity, efficiency, and land use [24]. However, palm planting may cause more severe man/land crises and food challenges. The biodiesel produced also has the disadvantages of high viscosity, high density, and low volatility [25], which can be alleviated by adding proper additives. Moreover, we found that little attention has been paid to the performance of palm oil biodiesel under engine idling conditions. In this study, 0, 5, 10, and 15% ethanol were added to pure palm oil biodiesel as the fuel of an engine to explore the effects of ethanol additives on the combustion, emission characteristics, and engine performance under idling conditions.

2. Experimental Setup and Procedure

2.1. Test Fuels

In this work, ethanol with 99.9% purity was used as an additive at different proportions when blended with pure palm oil biodiesel. Ethanol was added into biodiesel at volume ratios of 0%, 5%, 10%, and 15%, corresponding to B100 (100% biodiesel + 0% ethanol), B95E5 (95% biodiesel + 5% ethanol), B90E10 (90% biodiesel + 10% ethanol), and B85E15 (85% biodiesel + 15% ethanol). The fuel properties are shown in Table 1. The density, calorific value, viscosity, and cetane number of the biodiesels are greater than those of ethanol, but the oxygen content in ethanol is more than three times that of biodiesel. These differences in properties result in different combustion and emission characteristics.

Table 1. Fuel properties.

Properties (Units)	B100	B95E5	B90E10	B85E15	Ethanol
Density (kg/m^3 at 15 °C)	877	873.12	869.24	865.36	799.4
Calorific value (MJ/kg)	39.72	39.19	38.66	38.12	28.18
Oxygen content (%)	11.26	12.43	13.6	14.78	34.7
Viscosity (mm^2/s at 40 °C)	4.56	-	-	-	1.10
Cetane index	57.3	-	-	-	8
Flash point (°C)	196	-	-	-	12

2.2. Test Engine and Operating Methods

The engine tested in this study is a turbocharged four-cylinder CRDI diesel engine with a displacement of 1991 cc and with the exhaust after-treatment device removed. The engine specifications are listed in Table 2. The engine speed and load were controlled by an eddy current dynamometer (DY-230 kW, Hwanwoong Mechatronics, Gyeongsangnam-do, Korea). The pressure in the cylinder was measured by a piezoelectric pressure sensor (Type 6056A, Kistler Korea Co., Ltd., Gyeonggi-do, Korea) and recorded on a data acquisition board (PCI 6040e, National Instruments, Austin, TX, USA). The fuel consumption of the engine was determined using a high-precision digital electronic weighing balance (GP-100K, A&D Co., Ltd., Tokyo, Japan). MK2 (GreenLine MK2, Eurotron (Korea) Ltd., Seoul, Korea) and HPC-501 (Nantong Huapeng Electronics Co., Ltd., Jiangsu, China) multi-gas analyzers were used to measure CO, HC, and NOx emissions. The smoke opacity of the exhaust gas was measured by an OPA-102 smoke meter (QROTECH Co., Ltd., Gyeonggi Province, South Korea). The engine speed was set at 750 rpm to simulate idling, and the load was set to 30, 40, and 50 Nm to simulate the operation of vehicle accessories. Pilot injection timing was adjusted to 18 °CA BTDC, and the main injection timing was at 5 °CA BTDC. The injection pressure was fixed at 350 bar. The engine operating environment was maintained at 25 °C, and the cooling water temperature was 85 °C when the engine was running smoothly. The experimental and operating conditions are shown in Table 3. Figure 1 illustrates the engine test system.

Table 2. Specifications of the test engine.

Engine Type	4-Cylinder 4-Stroke Direct Injection
Fuel injection system	Bosch common-rail
Air system	Turbocharger with WGT
Bore (mm) × Stroke (mm)	83 × 92
Displacement (cc)	1991
Compression ratio	17.7:1
Max. power (kW/rpm)	82/4000
Injector hole diameter (mm)	0.17

Table 3. Experimental and operating conditions.

Test Fuels	B100, B95E5, B90E10, B85E15
Engine load	30, 40, 50 Nm
Engine speed	750 rpm
Fuel injection pressure	350 bar
Pilot injection timing	18 °CA BTDC
Main injection timing	5 °CA BTDC
Intake air temperature	25 ± 3 °C
Cooling water temperature	85 ± 3 °C

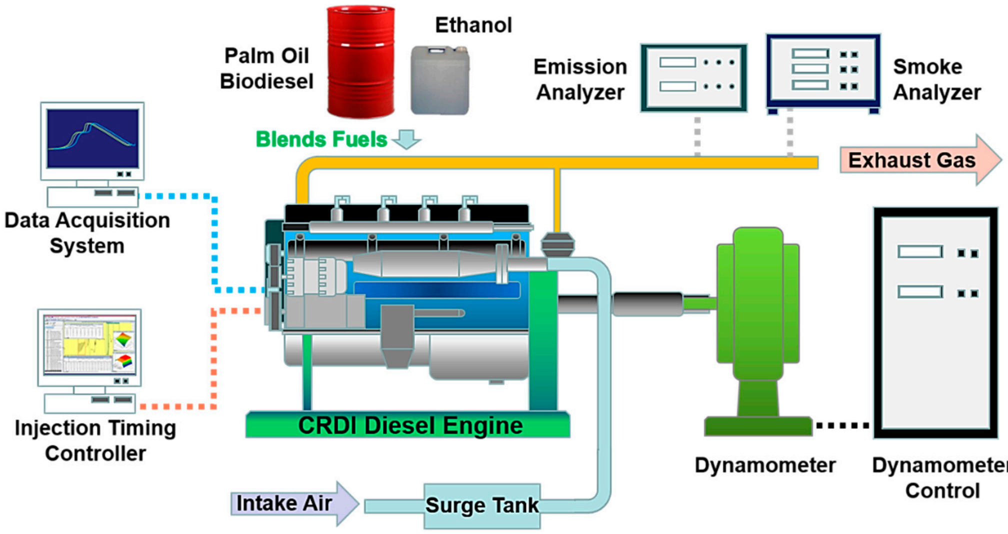

Figure 1. Engine test system.

3. Results and Discussion

3.1. Combustion Characteristics

The variations in cylinder pressure (CP) and heat release rate (HRR) of fuels with different concentrations of ethanol are shown in Figure 2. The combustion-related information from the CP and HRR graphs including ignition delay, combustion duration, in-cylinder peak pressure, and peak heat release rate is summarized in Table 4. For all fuels, high loads increase the peak cylinder pressure (CPmax) and maximum heat release rate (HRRmax). When the load was increased from 30 to 50 Nm, the peak pressure in the cylinder increased by 11.8% with B100, 13.3% with B95E5, 12.7% with B90E10, and 12.6% with B85E15. Additionally, the CPmax and HRRmax values of ethanol-biodiesel are larger than those of pure biodiesel, and the peak values increase with increasing ethanol concentration. There was little difference in ignition delay at idling speed, but this reflects an obvious trend. The ignition delay of the fuels decreases with increasing load, but ethanol extends this duration. The variation of combustion duration is opposite that of ignition delay, and ethanol slightly shortens the combustion duration. For instance, the combustion of pure biodiesel at 30 Nm lasts 20.95 °CA, and 15% ethanol shortens this phase to 19.55 °CA.

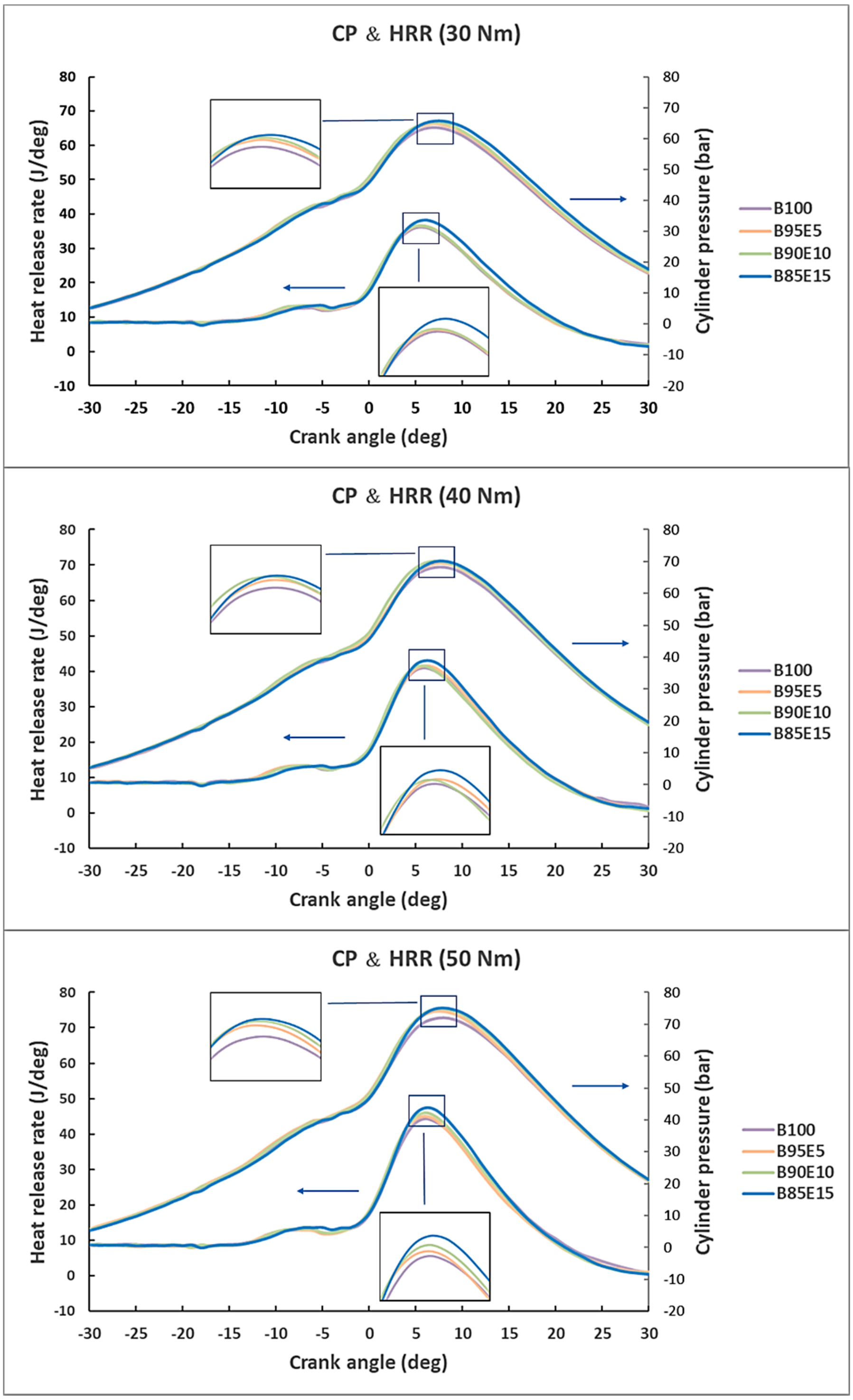

Figure 2. CP and HRR values of the blends.

Table 4. CPmax, HRRmax, ignition delay, and combustion duration values of the blends.

Fuel	Load (Nm)	CPmax (bar)	HRRmax (J/deg)	Ignition Delay (°CA)	Combustion Duration (°CA)
B100	30	65.2	31.27	5.45	20.95
	40	69.3	36.69	5.4	21.35
	50	72.9	39.23	5.3	22
B95E5	30	66.4	31.57	5.65	20.4
	40	70.5	37.07	5.55	21.35
	50	74.6	41.13	5.43	21.17
B90E10	30	66.8	31.77	6.15	20
	40	71	37.15	6	20.4
	50	75.3	42.31	5.8	21
B85E15	30	67.1	33.73	6.6	19.55
	40	71.2	38.93	6.55	20.4
	50	75.6	43.8	6.05	20.95

Adding ethanol, with a lower cetane number than biodiesel, reduces the cetane number of blended fuels. When ethanol evaporates, it absorbs heat in the cylinder, reduces the temperature in the cylinder, and extends the ignition delay of the blended fuel [17,26,27]. Therefore, the fuel with the highest ethanol content has the longest ignition delay under various conditions, which is consistent with previous findings [17,27]. A long ignition delay provides a longer fuel–air mixing period, which promotes higher CPmax and HRRmax. The oxygen content of the ethanol used in the test was as high as 34.7%, which increases the oxygen concentration in the fuel and is conducive to improved premixed combustion [26]. The viscosity and density of the blended fuels are better than those of pure biodiesel, and fuel injection atomization has a positive effect. Ethanol can shorten the fuel breakup length, increase the spray angle, refine the sprayed droplets, and help improve the degree of mixing [28], which helps to optimize combustion quality. The higher oxygen content in the ethanol-biodiesel blends spray reduces pyrolysis, increases oxidation, and improves diffusion combustion, shortening the combustion duration [17]. A longer ignition delay can cause greater fuel consumption in the premixing period and lesser consumption during diffusion combustion, resulting in a shorter combustion duration as ethanol content increases [29].

3.2. Engine Performance

The variation in braking-specific fuel consumption (BSFC) with ethanol volume and load is depicted in Figure 3. The difference in fuel calorific value shown in Figure 3 is the key to this trend. The calorific value of the blended fuel decreases with the increasing amount of ethanol. Therefore, under the same load, a fuel with a high ethanol concentration often must be injected at a larger volume to compensate for the effects of calorific value [26].

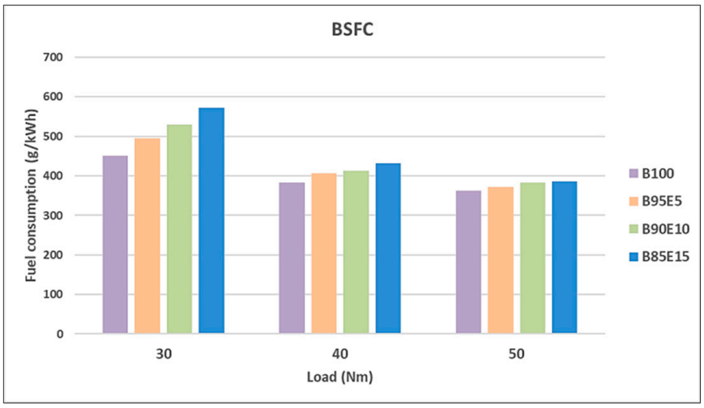

Figure 3. Braking-specific fuel consumption (BSFC) of blended fuels under loads of 30, 40, and 50 Nm.

As illustrated in Figure 4, the ethanol in fuel reduces the braking thermal efficiency (BTE) proportional to the volume of ethanol contained. The calorific value of ethanol and the larger latent heat of vaporization result in a lower temperature in the cylinder, which is not conducive for thorough combustion [30]. This negative effect is slightly weakened by a load increase. Compared with pure biodiesel, the BTE values of 5, 10, and 15% ethanol at a load of 30 Nm were reduced by 8.9, 14.9, and 21.2%, respectively, but the decreases were reduced to 2.3, 5.3, and 5.9% at a load of 50 Nm.

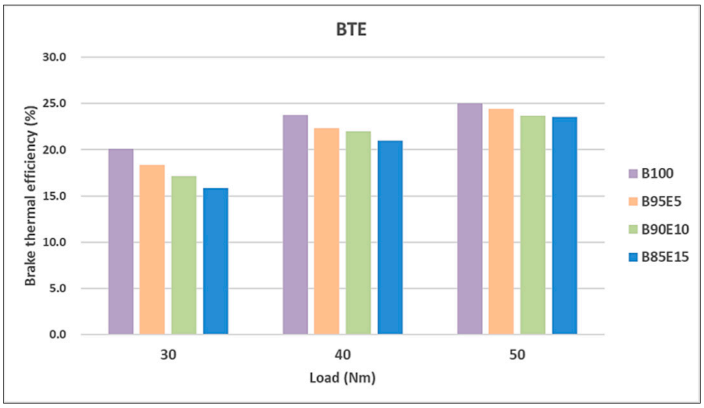

Figure 4. Braking thermal efficiency (BTE) of blended fuels under loads of 30, 40, and 50 Nm.

The coefficient of variation of indicated mean effective pressure (COVimep) reflects the cyclic variation of engine combustion, and a variation coefficient less than 10% is acceptable because a low coefficient of variation indicates stable combustion quality. The coefficient of variation of each fuel for 200 cycles is shown in Figure 5. The maximum COVimep of B100 can reach 2.3%, but the COVimep of the blended fuels after adding ethanol is lower than 1.67%. Some studies [31,32] have pointed out that the increase in ethanol content increases the COVimep of the fuel, but the performance observed under this test condition is different. The effect of ethanol on combustion improvement under idling conditions is obvious, similar to previous experimental results [27]. Fuel with a higher concentration of ethanol tends to be more stable, especially at 50 Nm, where the COVimep values of the four fuels are more similar to each other, which means that the advantages of the ethanol-biodiesel blends are diminished.

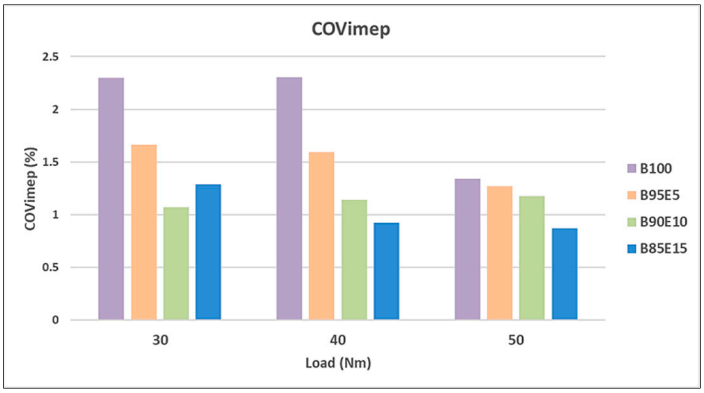

Figure 5. COVimep of blended fuels under loads of 30, 40, and 50 Nm.

The exhaust gas temperature (EGT) shown in Figure 6 provides information about the combustion process. At 30 Nm, the exhaust temperatures of B100, B95E5, B90E10, and B85E15 were 194, 193, 193, and 194 °C, respectively. After the load increased to 50 Nm, the exhaust temperatures of these four fuels increased to 244, 246, 245, and 242 °C, respectively. The exhaust temperature increases with increasing load, but the effect on exhaust temperature caused by ethanol is minimal, which is consistent with a previous finding [4].

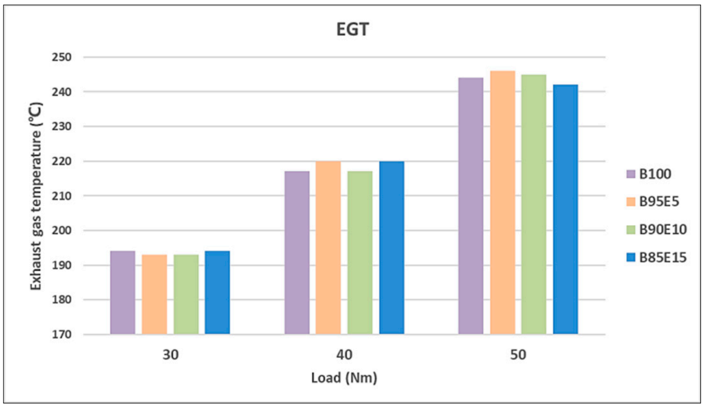

Figure 6. Exhaust gas temperature (EGT) of blended fuels under loads of 30, 40, and 50 Nm.

3.3. Emissions Characteristics

The CO emissions from the engine are shown in Figure 7. Obviously, the CO emissions of all fuels decrease as load increases. This might be because the pressure in the cylinder increases with load, and a larger pressure in the cylinder is conducive to more complete fuel combustion, which is consistent with the variation in cylinder pressure peak reported previously [3]. Under all tested loads, all ethanol-containing fuels showed good CO emission reduction effects. However, under loads of 30 and 40 Nm, CO emissions slightly increased with increasing ethanol concentration. This is because the ethanol in the blended fuel contains a large amount of hydroxyl groups, and the release of hydroxyl groups in the cylinder is beneficial to the oxidation of CO to CO_2, thereby reducing the presence of CO [3]. However, the higher latent heat of vaporization of ethanol reduces the gas temperature in the cylinder [26,33] and complete oxidation of CO cannot be achieved [33]; fuels with higher concentrations of ethanol at low loads produce higher CO emissions.

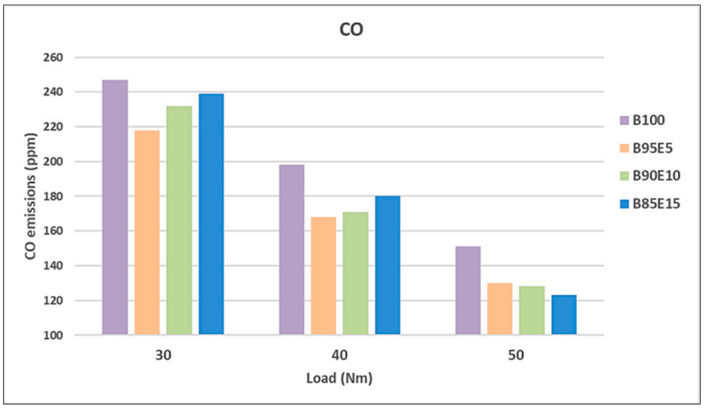

Figure 7. CO emissions of blended fuels under loads of 30, 40, and 50 Nm.

Figure 8 illustrates the HC emission characteristic of the fuels. The HC emissions of the four fuels increased as load increased from 30 to 50 Nm. The low-load ignition delay is longer, allowing better entrance of the oil and gas mixture into the cylinder gap, which intensifies the narrow gap effect. The increasing fuel injection quantity with increasing load and the narrow gap effect promote the formation of greater HC emissions [34]. Furthermore, the addition of ethanol encourages the generation of HC, and HC displacement is positively correlated with ethanol volume concentration. Yilmaz et al. explored the effect of ethanol concentration on HC produced by blended fuels and observed a similar trend. They explained that the cooling effect of ethanol at a high concentration is dominant under a low load, and only at a low concentration can it exert the advantage of its high oxygen content [35].

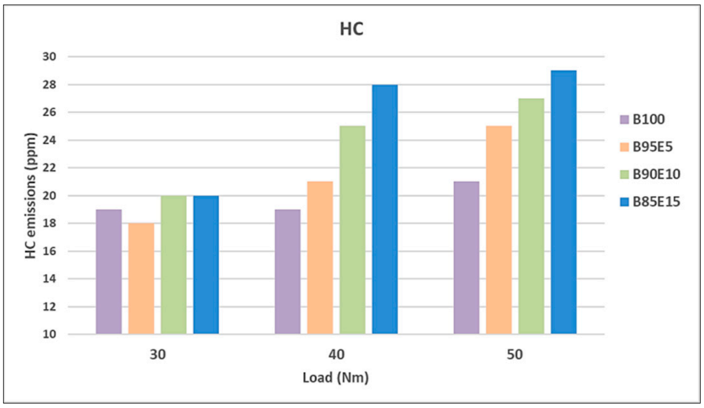

Figure 8. HC emissions of blended fuels under loads of 30, 40, and 50 Nm.

Figure 9 shows the NOx emission characteristic of the fuels. The addition of ethanol to biodiesel promotes the formation of NOx, and the amount of NOx emissions is positively correlated with the concentration of ethanol. The lower cetane number of ethanol extends the ignition time. As the ethanol concentration in the fuel increases, the cetane number of the blended fuel also increases, and the ignition delay becomes longer. It is beneficial to the air–fuel mixture to release heat faster, leading to an increase in temperature and enhanced NOx emissions [36]. Meanwhile, ethanol increases the oxygen content of the blended fuel, which also helps to increase the combustion temperature [37]. The NOx emission characteristics had similar results under loads of 30, 40, and 50 Nm. Among them, the promotion effect of ethanol on NOx was most obvious at 40 Nm. Concentrations of 5, 10, and 15% ethanol increased the NOx emissions by 15.9, 19.7, and 22.1%, respectively, as shown in Figure 9.

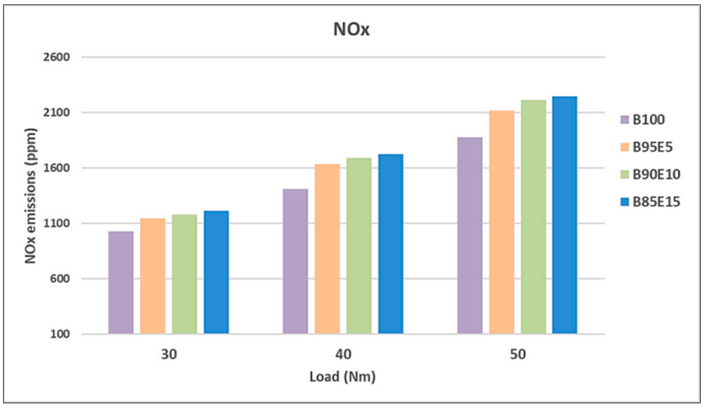

Figure 9. NOx emissions of blended fuels under loads of 30, 40, and 50 Nm.

The contribution of ethanol to smoke reduction is significant, as shown in Figure 10. As load increases, more fuel is injected into the cylinder, resulting in a greater equivalence ratio and greater fuel-rich area [38]. Therefore, a higher load promotes the formation of smoke from pure biodiesel. After adding ethanol, the smoke emissions of blended fuels are distinctly reduced, and as ethanol content increases, the reduction in emissions is greater. Ethanol increases the oxygen concentration in blended fuel and improves the combustion quality. Its lower carbon/hydrogen ratio inhibits the formation of particles and facilitates the oxidation of particles [26]. The greater latent heat of vaporization of ethanol reduces the temperature in the cylinder, and the longer ignition delay of the blended fuel is conducive to better mixing of oil and gas [26]. The smoke emissions of the ethanol-biodiesel blends did not increase with increasing load like they did in pure biodiesel. Ethanol had the greatest emission reduction effect under a load of 50 Nm, where 15% ethanol contributed a maximum reduction of 71%.

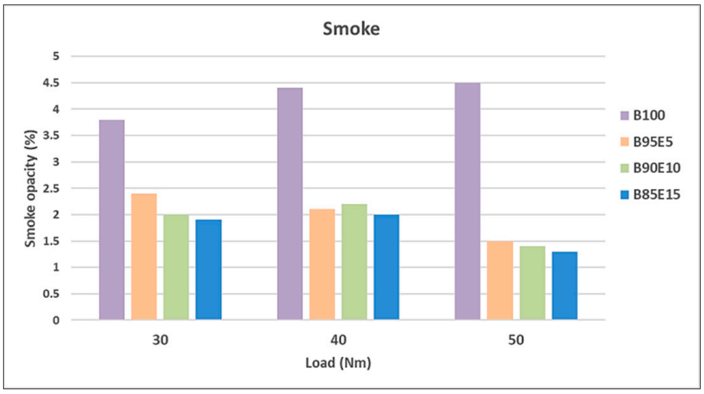

Figure 10. Smoke opacity values of blended fuels under loads of 30, 40, and 50 Nm.

4. Conclusions

In order to study the engine performance and combustion and emission characteristics of diesel engines at idle speed (750 rpm) with various low engine loads (30, 40, and 50 Nm), a series of experiments were carried out on a CRDI diesel engine fueled with ethanol-biodiesel blends containing 0, 5, 10, and 15 vol% ethanol additives. The main findings are summarized as follows:

As the load increases at idling speed, the peaks of CP and HRR increase; additional ethanol also helps increase the peaks. The results showed that the maximum increase in CPmax for adding 5, 10, and 15 vol% ethanol is 2.33%, 3.29%, and 3.7%, respectively, and the heat release rate is 4.83%, 7.82%, and 11.64%.

- Although the addition of ethanol significantly enhances the BSFC, increasing the load can reduce it. The trend of BTE is opposite that of the BSFC as it decreases with increasing load and with increasing ethanol concentration. Increasing the ethanol content and load reduces the COVimep. EGT also increases significantly with increasing load, but the effect of ethanol is not obvious.

- Ethanol additives have an attenuation effect on CO and especially smoke. The maximum smoke reduction of the blends fuel with 15vol% ethanol additive reached 71%. The greater the load of ethanol, the more obvious the effect on smoke reduction. On the contrary, increases in load and ethanol content promote the generation of HC and NOx emissions.

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Data Availability Statement: The data presented in this study are available on request from the corresponding author.

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